Scalable Lateral Mixing and Coherent Turbulence DRI: Use of an AUV to Quantify Submesoscale Mixing Processes

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LONG-TERM GOALS

The long-term goal of this project is to quantify the driving mechanisms and pathways of dissipation of lateral submesoscale mixing. A major thrust is understanding the role that cascade processes, both forward and backward, play in connecting submesoscale variability to 3D turbulence.

OBJECTIVES

The objective of this experiment is to provide in situ data to test the validity of three major lateral mixing hypotheses developed by the ONR LatMIX DRI May 2008 Boston working group. These hypotheses are that:

(H-I) "inhomogeneous IW mixing creates PV anomalies that are responsible for significant isopycnal mixing";

(H-II) "mesoscale straining leads to a cascade of both tracer and PV variance to submesoscales that is responsible for significant submesoscale isopycnal mixing";

(H-III) "non-QG, submesoscale instabilities feed a forward cascade of energy, scalar and PV variance which enhances both isopycnal and diapycnal mixing".

Our work is aimed providing data and then performing scientific analyses to examine the validity of these hypotheses. To that end, we are addressing the following questions:

(1) What is the role of small scale turbulence in lateral mixing? It is a source (H-I) or sink (H-III) of lateral mixing?

(2) What is the nature of the scalar spectra along isopycnals (dye, spice) between the submesoscale and the microscale?

(3) Is there a constant strain rate driving a forward cascade of scalar variance?

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14. ABSTRACT
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15. SUBJECT TERMS

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APPROACH

(1) Observational approach

The observational approach is to use the Autonomous Underwater Vehicle, T-REMUS, shown in Fig. 1. T-REMUS is a custom designed REMUS 100 vehicle manufactured by Hydroid Inc., containing the Rockland Microstructure Measurement System (RMMS), an upward and downward looking 1.2 MHz ADCP, a FASTCAT Seabird CTD, and a WET Labs BB2F Combination Spectral Backscattering Meter/ Chlorophyll Fluormeter. In addition, the vehicle contains a variety of "hotel" sensors which measure pitch, roll, yaw, and other internal dynamical parameters.

This suite of sensors on T-REMUS allows quantification of the key dynamical and kinematical turbulent and submesoscale physical processes. The turbulence measurements are made concomitantly with very high spatial resolution measurements of velocity shear, temperature, salinity, and depth. The parameters which can be estimated from the data collected by the T-REMUS include: the turbulent velocity dissipation rate, ε, the temperature variance dissipation(diffusion) rate, χ, the local buoyancy frequency, N, and vertical shear, $\frac{du}{dz}$, and thus using the latter two quantites the Richardson (Froude) number $Ri = \frac{N^2}{(\frac{du}{dz})^2} = Fr^{-2}$. In addition we obtain simultaneously the local submesoscale fields of velocity salinity, density, fluorescein, chlorophyll-a and optical (700nm) scattering (Goodman & Wang, 2009; Wang & Goodman, 2009a, b) in which the turbulence is embedded.

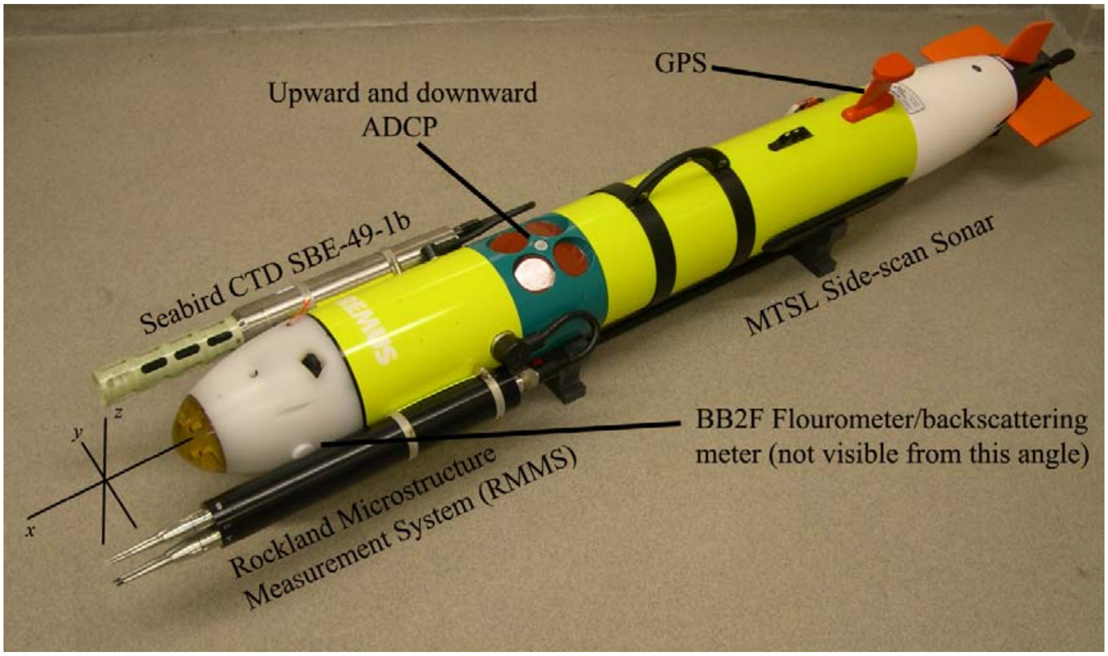

Figure 1, The SMAST T-REMUS Autonomous Underwater Vehicle. It is 2.0 m long, 20 cm diameter, and 63kg mass. Vehicle based sensors are indicated in the figure.

(2) Theoretical Context: Submesoscale, IW, and 3D Turbulence Scalar Spectral Power Laws

Central to quantifying ocean mixing is the relationship of essentially two dimensional QG like submesoscale variability which produces along isopycnal mixing to that of three dimensional turbulence which produces across isopycnal mixing. Strongly related to this is the nature of the scalar variance spectral wavenumber cascade. Numerical studies such as that of Molemaker et al. (2005), and Thomas et al. (2007) suggest a forward scalar variance cascade within the submesoscale due to mesoscale straining. This is hypothesized to result in a "Batchelor" like -1 power law for the scalar variance wavenumber spectrum. Thus, a key factor in addressing the three LatMIX major hypotheses, shown above, and in quantifying lateral along isopycnal mixing, is the nature of the scalar wavenumber spectra and the scalar variance cascade process. One of our principle scientific foci will be on this.

A remarkable accomplishment of quasi equilibrium turbulence theory has been the development of the -5/3 law and – 3 law for the kinetic energy wavenumber spectra of 3D and 2D (QG) turbulence, respectively. These laws are based on ideas originally developed by A. N. Kolomogorov (1941) and then later by G. K. Batchelor (1953). Their experimental and numerical verification is one of the great scientific accomplishments of the past several decades. These spectral formulations are based on a combination of nonlinear cascade physics and dimensional analysis (Vallis, 2006). In the 3D turbulence case the rate of transfer of kinetic energy (KE) is constant and equal to ε, the turbulent dissipation rate with non linear 3 D processes resulting in KE being cascaded in the forward direction to smaller scales and higher wavenumbers. Note, however, that ε has two separate meanings. It is both the amount of kinetic energy which is eventually dissipated and it is also the rate of transfer of kinetic energy from larger turbulent scales to the mid range turbulent scales and then on to the smaller scales (Tennekes and Lumley, 1972). For the 2D QG turbulence case, as a result of potential vorticity conservation, non linear processes result in enstrophy being cascaded in the forward direction at some constant rate, ψ. This results in KE being cascaded in the inverse direction to larger scales and lower wavenumbers. Thus ψ in QG turbulence plays the same type of role as a constant cascade parameter as ε does in 3D turbulence. It is straightforward to show that the rate of transfer of KE in QG, 2 D turbulence, ε is not constant over this wavenumber regime.

These same quasi equilibrium cascade concepts can be applied to the scalar spectra. Let χ be the rate of transfer of some scalar such as temperature and salinity. If we assume an equilibrium subrange for the scalar spectra, then χ must be constant in this wavenumber subrange. From just dimensional scaling the wavenumber scalar spectra Φ must take the form

(1) $$\Phi = A\frac{\chi}{S}k^{-1} \qquad \text{for} \qquad \kappa_u < \kappa < \kappa_l$$

(Kraichnan, 1967), where A is a universal constant of order 1; χ, the rate of transfer of scalar variance, has units $\mathbf{\frac{(scalar\ units)^2}{time}}$ and S is the local strain rate, which has units of $(\text{time})^{-1}$. In equation (1) S is the key cascade parameter. In this analysis we will take our spectra as referring to the 1D (measurable) horizontal wavenumber spectra.

In the 3D turbulent case the inertial subrange strain rate, S, must scale with the constant transfer rate of kinetic energy, ε and only local wavenumber (Batchelor, 1953, Tennekes and Lumley, 1972), resulting in

(2) $$\Phi = A\frac{\chi}{\varepsilon}k^{-\frac{5}{3}} \qquad \kappa_e < \kappa < \kappa_\nu$$

while in the diffusive subrange S must scale with the local strain rate produced by the larger scale eddies in the inertial subrange

(3) $$\Phi = B\chi(\frac{\varepsilon}{\nu})^{-\frac{1}{2}}k^{-1} \qquad \kappa_\nu < \kappa < \kappa_B$$

where κ_e , is the energy containing wavenumber limit, κ_ν the Kolomogorv wavenumber limit, and κ_B ,the Batchelor wavenumber limit. Note that the constant B can be obtained in terms of A by setting the two forms of the wavenumber spectra given by (2) and (3) equal at the wavenumber boundary κ_ν. The well known and well verified spectral forms (2) and (3) represent the scalar inertial and diffusive subranges produced by 3D turbulence (Dillon and Caldwell, 1980).

These ideas can be extended to the submesoscale regime for the case of variability modeled as 2D QG turbulence. Taking S as the mesoscale strain rate we see that equation (1) then describes the scalar spectrum in the submesoscale which can be thought of as a "Batchelor" spectra with the mesoscale strain rate S replacing the 3D turbulent strain rate $(\frac{\varepsilon}{\nu})^{\frac{1}{2}}$ of equation (3). Recent results of Ferrari (ONR LatMIX Boston workshop, 2008) and others (Rudnick, 2001) suggest that "spice" spectra in the submesoscale follow the -1 power law of equation (1) and support theoretical concepts of Molemaker et al. (2005) and Thomas et al.(2007) and that it is the mesoscale strain rate S which results in the scalar variance forward cascade into the submesoscale.

Internal wave induced vertical displacements of a scalar gradient such as that of temperature and salinity can also result in scalar variability. One of the great accomplishments of the past 30 years has been the near universal nature of the Garrett and Munk (1975) model in describing IW spectral forms, although it should be noted that very limited horizontal spectral measurements of internal wave have been made. The GM models predict that scalar variance spectra would go as

(4) $$\Phi = E_\phi k^{-2} \quad \text{for} \qquad \kappa_0 < \kappa < \kappa_c ,$$

where κ_0 , κ_c are the wavenumber limits of the internal wave filed, determined by the source and sink of internal wave energy. In equation (4) E_ϕ has units of $\frac{\textbf{(scalar units)}^{\mathbf{2}}}{\textbf{length}^{\mathbf{-1}}}$. One of the most important recent theoretical and observational results is in relating GM type internal waves to turbulent dissipation rate, ε (Henyey, 1986, Gregg, 1989, Polzin, 1995) and that

(5) $$\varepsilon \propto E_\phi{}^2$$

This is related to the fall off of the spectra beyond $\kappa > \kappa_c$ where

(6) $$\Phi = \frac{E_\phi}{k_c}k^{-3}$$

From vertical microstructure profilers strong observational support for (5) and (6) occurs for the vertical 1D wavenumber spectra of temperature. No conclusive set of observations have shown the validity of (6) for the horizontal wavenumber spectrum.

However, recently Klymak and Moum (2007a,b) did attempt to examine the nature of the horizontal wavenumber spectra over the internal wave and submesoscale ranges of 1 m to 1 km. They found some limited evidence of (6) but for the most observed that the horizontal wavenumber spectrum seemed to follow equation (2). This is an unexpected result since in this wavenumber regime 3D turbulence is expected to be highly anisotropic, which some have argued in analogy to the atmospheric case (Lumley, 1964,Weinstock,1985, Holloway, 1986) should result in a “buoyant” subrange with the spectra following a -3 power law as in equation (6). Moreover the type of measurements performed by Klymak and Moum (2007a, b), towing an instrumented body at 1 m/sec at essentially constant depth, are susceptible to finestructure contamination. This would result in flattening a -3 power law into a power law closer to -5/3 (Goodman, 1978).

Performing scalar measurements such as temperature and salinity along an isopycnal (spice) and at the same measuring the displacement of the isopycnal and the turbulent fields would be a clear way of distinguishing these mechanism and sorting out the different contributions of submesoscale variability, internal waves, and 3D anisotropic turbulence in producing along and across isopycnal mixing, which is critical to examining the nature of submesoscale mixing. The T-REMUS vehicle is near ideal for doing this.

WORK COMPLETED

In the past year, we have focused on upgrades to the T-REMUS AUV. We have installed a Wetlabs triple puck fluorometer/optical scattering sensor system, a wireless surface communication network, and an underwater two way communication system. The Wetlabs system will allow us to perform in situ measurements of fluorescein dye. This will then permit us to track in situ dye deployment experiments for use in direct measurements of horizontal and vertical diffusion. The T-REMUS at the time of this writing resides at Hydroid Inc. for hardware (Recon system) and software upgrades to allow two way communication with our new drogued Gateway navigation buoy system. Fig 2. shows a cartoon depiction of this system, embedded in a hypothetical future LatMIX experiment. Note that the Gateway buoy is attached to a drogued leader buoy. This configuration minimizes the Gateway submergence due to surface wave down wash. The Gateway buoy allows a real time tracking and control of T-REMUS. The leader buoy will be drogued at depth (below mixed layer) to allow tracking of submesocale features. To our knowledge this is the first time that an AUV has been used in this configuration. We are preparing to participate in the LatMIX DRI 2010 “East Coast“engineering” experiment. Close coordination with the Ledwell et al. dye experiment team is occurring.

We have now had 5 years of experience in both the engineering and scientific applications of using the T-REMUS vehicle. We have used T-REMUS in two major scientific experiments. These are: (1) the NSF sponsored MerMade program (MacDanld et al. 2007) ; and (2) the ONR LOCO program (Goodman and Wang, 2009; Wang and Goodman, 2009a, b). We are in the process of examining data on hand to infer the nature of mixing efficiency from simultaneous estimates of ε and χ. Results of this analysis could be significant in determining the viability of LatMix Hypothesis I, which requires that the density mixing scars of turbulence are sufficiently strong to drive submesoscale vortices. To date our result suggest very low mixing rates in strong turbulence.

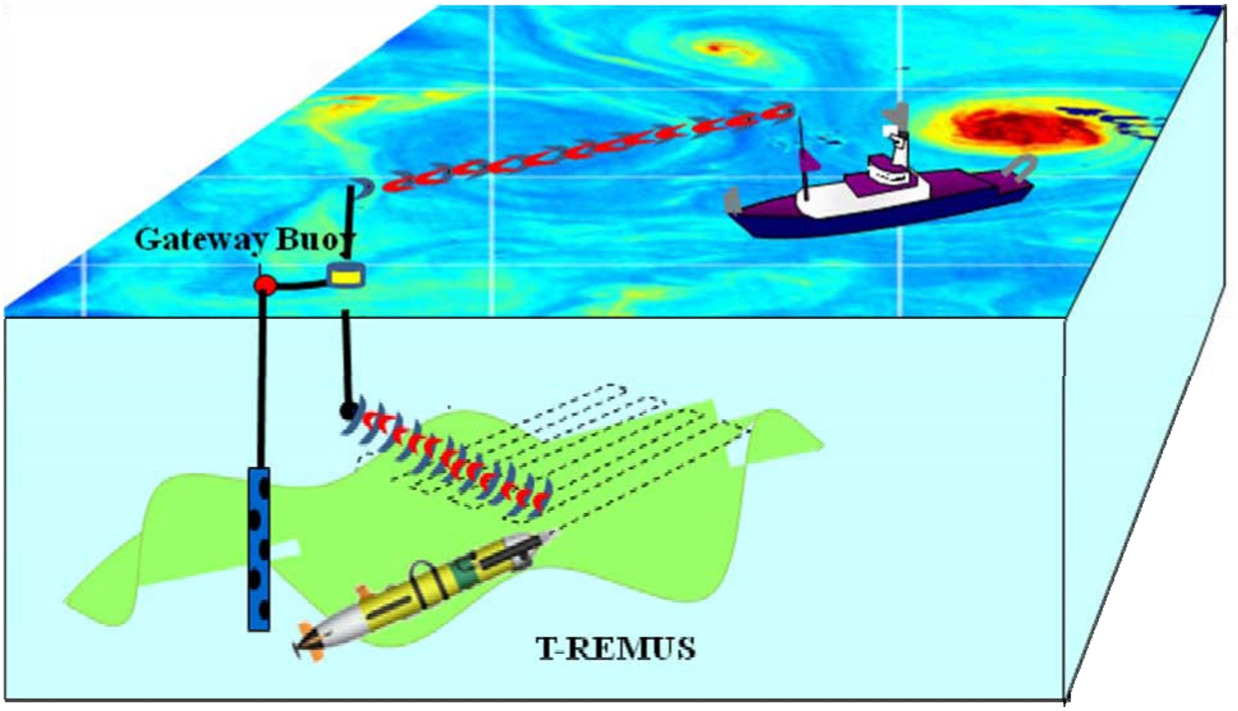

Figure 2, Schematic map of the T-REMUS deployments for the LATMIX DRI 2010 experiment. The T-REMUS AUV will follow the Gateway Buoy by means of an attached drogue buoy.

REFERENCES

Batchelor, G.K. Theory of homogenous Turbulence, Cambridge University Press, 1953

Dillon, T. M., and D. R. Caldwell, 1980: The Batchelor spectrum and dissipation in the upper ocean. *J. Geophys. Res.*, **85,** 1910–1916.00

Garrett ,C.J.R. and W. H. Munk, 1975, Space-time scales of internal waves: A progress report, J. Geophys. Res. 80, 291-297

Goodman, L. 1978, On the Time Dependence of a Scalar Undergoing Advection, J. PHYS. Oceanogr., Vol. 8, No.5.

Goodman, L. , E. Levine, and R. Lueck, 2006, On Closing Turbulence Budgets from an AUV, J. Atoms. Ocean. Tech. 23, 977-990, July 2006

Goodman, L. and Robinson, A.R. On the Theory of Advective Effects on Biological Dynamics in the Sea, III: The Role of Turbulence in Biological Physical Interactions, Proc Royal Soc., Proceedings A 464 (2091), Mar 08, 2008.

Goodman, L. and Z. Wang, June, 2009, Turbulence observations in the northern bight of Monterey Bay from a small AUV, Journal of Marine Systems, Volume 77, Issue 4, Special issue on marine turbulence, p441-458, ISSN 0924-7963, Doi:10.1016/j.jmarsys.2008.11.004

Henyey, F.S.J., J. Wright, and s.M. Flatte, 1986, Energy and Action flow through the internal wave field, j. Geophys. Res., 91, 8487-8595

Holloway, G., 1986: Considerations on the Theory of Temperature spectra in Stably Stratified Turbulence. *J. Phys. Oceanogr.*, **16**, 2179–2183.

Klymak, J.M., and J.N. Moum, 2007a: Oceanic Isopycnal Slope Spectra. Part I: Internal Waves. *J. Phys. Oceanogr.*, **37**, 1215–1231.

Klymak, J.M., and J.N. Moum, 2007b: Oceanic Isopycnal Slope Spectra. Part II: Turbulence. *J. Phys. Oceanogr.*, **37**, 1232–1245.

Kolmogorv, A.N., 1941, The local structure of turbulence in an incompressible viscous fluid for very large Reynolds numbers, C.R. Akad Nauk,SSR, 30 301-305

Kraichnan, R.H. 1967 Inertial ranges in two dimensional turbulence, Phys. Fluids, 10 1417-1423

Lumley,J.L. 1964 The spectrum of nearly inertial turbulence in a stably stratified fluid. J. Atmos Sci. 21, 99-102

MacDonald, D. G., L. Goodman, and R. D. Hetland, 2007, Turbulent dissipation in a near-field river plume: A comparison of control volume and microstructure observations with a numerical model, . , *J. Geophys. Res.*, 112,

Molemaker, M. J., J. C. McWilliams, and I Yavneh, 2005, Baroclinic instability and loss of balance, J. Phys. Oceanogr., 35, 1505-1517

Polzin,K.L.,J.M. Toole, R.W Shmitt, 1995, Finescale Parameterization of turblent dissipation, J. phys. Oceanogr. 25, 306-328

Rudnick, D.L., 2001, On the horizontal variability of the upper ocean, Proceedings Hawaiian Winter Workshop [12th] Held in the University of Hawaii at Manoa on January 16-19, 2001, 87-94.
Tennekes, H. and Lumley, J. L. A First Course in Turbulence, MIT Press, 1972

Thomas, L. N. Tandon, A., Mahaedevan, A., Submesoscale processes and dynamics, submitted 2007 J. Gepoophys. Res

Vallis, G.K. 2006, Atmospheric and Oceanic Fluid Dynamics: Fundamentals of Large-scale Circulation, Cambridge University Press

Wang, Z. and L. Goodman, January, 2009a, Evolution of the spatial structure of a thin phytoplankton layer into a turbulent field. Marine Ecology Progress Series. 374:57-74 Doi:10.3354/meps07738.

Wang, Z. and L. Goodman, 2009b, (in press). The evolution of a thin phytoplankton layer in strong turbulence. Continental Shelf Research, LOCO special issue.

Weinstock, J. 1985 On the Theory of temperature spectra in a stratified fluid, J. Phys. Oceanogr., 15, 475_47